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AGGREGATES AND SKID RESISTANCE

by

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the New Jersey Department of Transportation. This report does not constitute a standard, specification, or regulation.		
The goal of this study was to correlate the results of a laboratory test procedure measuring aggregate polish resistance with skid resistance in bituminous pavements. This correlation would be instrumental in identifying skid-resistant aggregates and would create the potential for measuring skid-resistance during aggregate procurement. This study was conducted in two phases. The first estimated the empirical relationship between aggregate microtexture and cumulative polishing using a modification of ASTM D-3319 and ASTM E-303. An exponential model was developed which realistically approximates the minimum polish value observed with the theoretical asymptote of the polishing rate curve. The magnitude of this asymptote, PV, correlated well with New Jersey's skid resistance experience with specific aggregate types and was subsequently used in the study's second phase. In the second portion of this study, a more detailed relationship between PV and polynomic skid resistance was sought. Experiments were conducted to evaluate polish values of aggregates and skid resistance of bituminous pavements composed of these aggregates, and to collect environmental data on selected skid test sites over a period of one year. This information was used to normalize the skid resistance of a bituminous pavement in terms of the aggregate's polish value and cyclical environmental factors. Additional research is required to develop and refine the models described in this report. This report concludes with a detailed description of the work to be accomplished in the final phase of this analysis and presents a statistical specification for the proposed skid-resistance of surface aggregates based on polish resistance.		
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16. Abstract The goal of this study was to correlate the results of a laboratory test procedure measuring aggregate polish resistance with skid resistance in bituminous pavements. This correlation would be instrumental in identifying skid-resistant aggregates, and would create the potential for assuring lifelong skid-resistant bituminous pavements. This study was conducted in two phases. The first estimated the empirical relationship between aggregate microtexture and cumulative polishing using a modification of ASTM D-3319 and ASTM E-303. An exponential model was developed which realistically approximates the minimum polish value observed with the theoretical asymptote of the polishing rate curve. The magnitude of this asymptote, PV, correlated well with New Jersey's skid resistance experience with specific aggregate types and was subsequently used in the study's second phase. In the second portion of this study, a more detailed relationship between PV and long-term minimum skid resistance was sought. Experiments were conducted to evaluate polish values of aggregates and skid resistance of bituminous pavements composed of these aggregates, and to collect environmental data on selected skid test sites over a period of one year. This information was used to normalize the skid resistance of a bituminous pavement in terms of the aggregate's polish value and cyclical environmental factors. Additional research is required to check and refine the models developed. This report concludes with a detailed description of the work to be accomplished in order to finalize this analysis and implement a statistical specification for the prequalification of surface course aggregates based on polish resistance.			
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Implementation Statement

This report presents the research results, analyses and recommendations pertaining to the use of the accelerated polishing test procedure as a prequalification test for aggregates proposed for surface course mixes.

The adoption of an acceptance plan would result in an upgrade of the current method used to approve aggregate sources and would further ensure longlasting, safe and skid-resistant pavements for the people of New Jersey. Significant steps were taken towards this goal in the study documented here, however, it was concluded that additional research work is necessary before implementation of an acceptance plan is warranted.

This study recommends attention to specific research areas, in order to promote future implementation of a surface course aggregate acceptance plan based on minimum polish value. These recommendations have been incorporated into an HPR-NJ research work plan, entitled "Skid Resistance Implementation Study", which is now pending Federal Highway Administration approval.

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1.0 Objective

The ultimate goal of this study is to develop and implement a laboratory acceptance procedure to prequalify aggregates used in the Department's bituminous surface course mixes, based on their long-term skid resistant qualities.

2.0 Research Methodology

This study was prompted by the need for a laboratory procedure capable of quantifying the skid resistance potential of aggregates proposed for use in bituminous surface course mixes. It would be of invaluable assistance to highway engineers if they could know, before a pavement was actually constructed, whether the proposed mix design was capable of providing a long term skid resistant pavement. This question has been addressed in many different ways over the years, and a number of qualitative methods for identifying bituminous mix designs with long term skid resistance potential have been used with some success. This study seeks to develop statistical models which may be used to evaluate the skid resistance potential of mixes prior to construction.

To accomplish this, the individual assignments include the design of an analytical method to evaluate laboratory test results, achieving an understanding of how skid resistance decays with time as well as an understanding of the seasonal influence on skid resistance by the environment,

and also developing correlations between laboratory and field measurements. These challenges were addressed in a battery of three distinct analyses as described below.

In the first, a mathematical model was developed to characterize the polish resistance of aggregates on the basis of an accelerated laboratory test. Using this test, the theoretical minimum (ultimate) polish value for each aggregate tested was determined.

Secondly, skid resistance, microtexture, macrotexture, and environmental data were collected on old, well-polished bituminous pavements. With this information, it was possible to estimate inherent skid resistance variability and to assess the effect of environmental factors on skid resistance. This information was subsequently used to develop a statistical model screening out environmental factors from the estimated terminal skid resistance of a bituminous pavement.

Finally, a relationship between the terminal skid resistance value produced by this procedure and the estimated asymptotic polish value of aggregates used in the mix was developed.

3.0 Background

The skid resistance of a pavement is dependent upon a number of factors, notably accumulated traffic, the surface texture, and the polishing characteristics of the aggregates.

A simplified explanation of the interaction between these factors is that traffic abrades the pavement surface, exposing the aggregates. The aggregate wears and becomes polished which, in turn, reduces skid resistance.

There are two generally accepted strategies for improving the long-term skid resistance of the roadway. The first technique -- one traditionally used in New Jersey -- is to modify the surface course mix design so as to provide the optimum macrotexture in the riding course. The second is to require the use of high quality, polish resistant aggregates which will provide durable aggregate texture in the riding course.

Since 1967, the NJDOT has been actively involved in the study of skid resistance. Initial research efforts were concerned with the in-situ measurement of skid resistance on bituminous and concrete pavements. This work led to the identification of poor quality aggregate types, and subsequent restrictions on their use in surface course mixes. From 1973, research concentrated on the development of mix design gradations which would produce a greater surface texture, thereby increasing skid-resistant characteristics. This work resulted in the New Jersey standard I-4 mix, the open-graded mix, and the crushed gravel friction course. Continuous study of pavement skid resistance and mix design characteristics led to further understanding of the complex

relationships between microtexture, macrotexture, and skid resistance.

Microtexture is defined as the surface roughness of individual aggregate particles, which depends largely on the mineral composition and number of fractured surfaces of the aggregate. The British Pendulum Test (ASTM E-303) is the standard method used to measure microtexture. Macrotexture is a function of aggregate gradation in the surface course and is measured in New Jersey using a modified Sandpatch Method (volume displacement of sand relative to that for a smooth surface).

These early research efforts resulted in the development of mathematical models which describe the skid resistance of a pavement, with various degrees of success, in terms of microtexture, macrotexture and other factors perceived to be significant (1). New Jersey's traditional model for skid resistance and texture is a simple multiple regression statement, which was derived from field tests on numerous and varied bituminous pavement surfaces over a long period of time. The sheer size of the data base used probably contributes to the high degree of correlation found for this relationship ($R^2 = 0.85$).

$$SN40 = 0.8 \text{ BPN} + 162.5 \text{ MTD} - 11.0$$

Eqn. 1

where SN40 = skid number at 40 mph

BPN = field measured British Pendulum Number

MTD = macrotexture (modified sandpatch)

It was initially expected that this model would be of use when laboratory measures of aggregate microtexture were to be statistically translated into estimates of overall pavement texture. This estimated lab-to-field relationship was found to be unsatisfactory.

A second look at the problem revealed that these original New Jersey experiments did not adequately account for a number of variables which affect the field measurements of skid resistance, microtexture, and macrotexture. First, an evaluation of the seasonal factors affecting these three variables was not included in the scope of this early work. Secondly, pavement age was belatedly identified as a critical parameter.

However, research recently completed by Nittany Engineers and Management Consultants, Inc. (2) for the Federal Highway Administration has shown some promise in accounting for the seasonal variations. This study has resulted in a procedure for adjusting skid resistance measurements made on a particular day to an estimated end-of-season minimum skid number based on average daily traffic, julian calendar day, dry-spell factor, and air temperature. A very good correlation was obtained for this relationship and it was anticipated that it could be directly applied to skid resis-

tance data from New Jersey.

Also, research conducted at Texas Transportation Institute (3) has attempted to integrate the pavement age factor, by describing skid resistance mathematically in terms of three parameters: the accumulated traffic, the aggregate polish value after nine hours of polishing, and the LA Abrasion factor. The poor correlation reported for this relationship is attributed to the variety of factors which influence the measurement of skid resistance, most notably seasonal variations and day-to-day weather conditions.

The conclusions drawn from these previous studies lead us to develop a probable scenario for changes that occur in a pavement surface as it is exposed to traffic over time. It is now believed that the influence of an aggregate's polishing characteristics on skid resistance are minimal until the bituminous matrix is sufficiently worn by traffic to expose the aggregate surface. Thus, it is not until the later stages of a pavement's service life, that aggregate microtexture becomes most essential in sustaining the skid resistance of the pavement. This brief statement on skid resistance and aggregate microtexture forms the nucleus of the study documented in the following pages. A more detailed examination of these ideas is presented in Section 4.0.

Aggregate resistance to the loss of microtexture, which is dependent on the polishing characteristics of each

particular aggregate, may be readily measured. The British Polishing Wheel and Pendulum Tester, respectively, simulate and measure the polishing action of traffic on aggregates at an accelerated rate. ASTM Specifications D-3319 and E-303 outline the procedures to be followed. According to a survey conducted in 1985 by ASTM Subcommittee D04.35, four states (Alabama, Louisiana, Texas and West Virginia) currently use this method to prequalify polish resistant aggregates for use in surface course mixes.

Generally, the acceptance procedure used is to polish the aggregate samples on the British Polishing Wheel, making British Pendulum tests at periodic intervals until a minimum British Pendulum Number (PV) is reached. In contrast, ASTM D-3319 notes that aggregates should be polished for ten hours, unless the minimum polish value is achieved in a shorter time.

It was observed early on that New Jersey aggregates would require a longer period of accelerated polishing before reaching a minimum polish value. Regional and geological considerations in New Jersey suggest that a more resistant aggregate is present here, and experience with these aggregates has been generally favorable.

The following quotation from the TTI study summarizes the significance of aggregate polishing characteristics on skid resistance:

"...it has been found that a reliable correlation does exist between the ultimate polish value of the aggregate reached in the laboratory test and the stable value of skid resistance reached in the field after several years of traffic." (3)

The relationships involving minimum polish value, environmental factors, traffic accumulation, and skid resistance developed in the several studies cited have proven helpful in the course of this study. Much of the experimental method and analytical procedures used in the present analysis were made possible by the contributions of these earlier works.

4.0 Consideration of Theoretical Models

A number of theories were postulated at the outset of this research study. Whether or not these hypotheses are supported by the data collected is the true test of their merit. Therefore, it will be helpful to identify the hypotheses made and reference the experiments conducted to test them.

A fundamental premise underlying the practical use of these hypotheses is that the elementary components of skid resistance are additive, although not necessarily linearly. That is, the skid resistance of a bituminous pavement at any point in time is a function of the inherent characteristics of the aggregates used in the mix, the cumulative effect of polishing, and a cyclical, seasonal effect. These effects are shown in Equation 2 and presented in Figure 1.

After 2 million vehicle passes, skid resistance fluctuates seasonally about a terminal value

SKID RESISTANCE

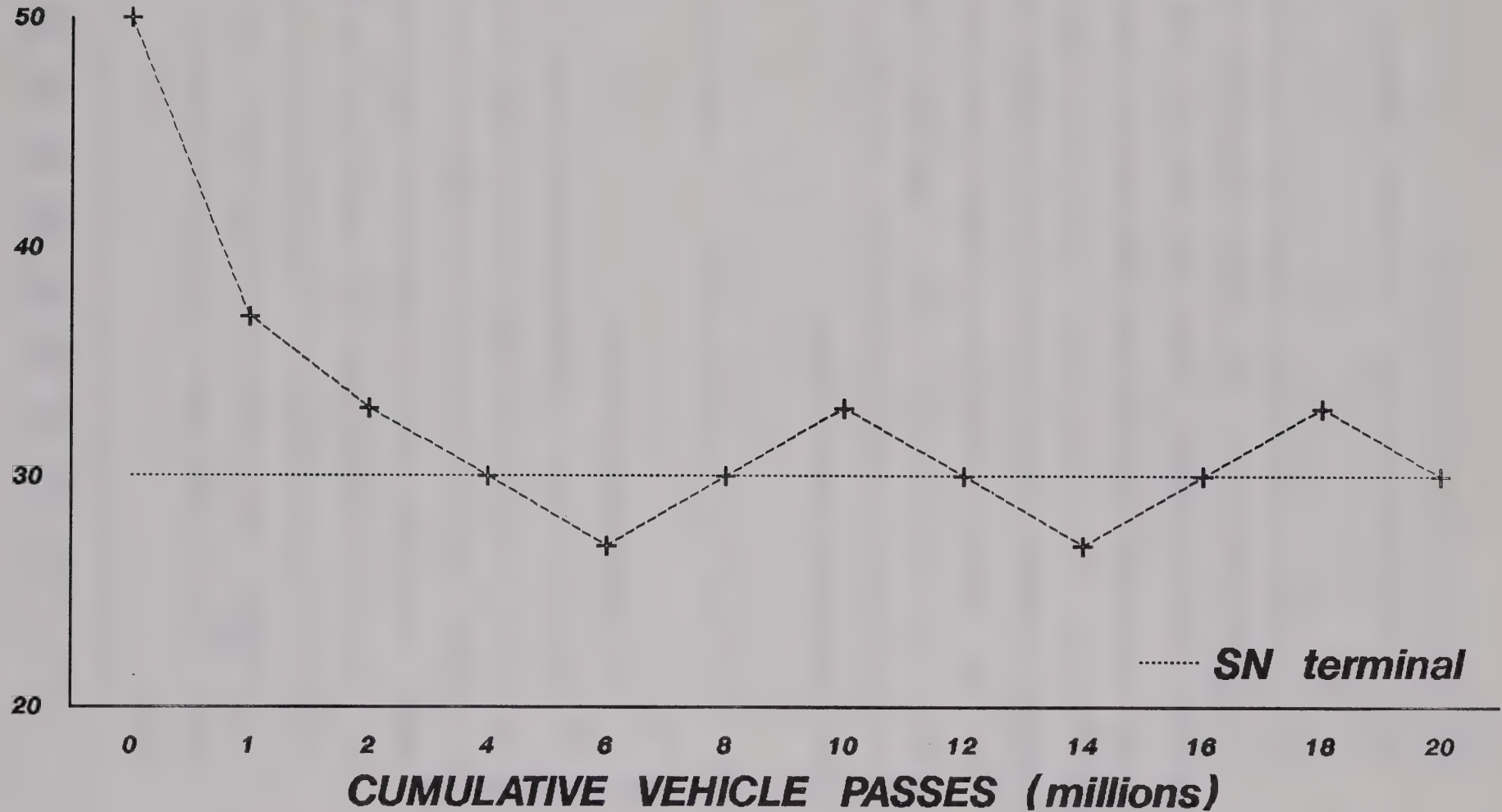


Figure 1

$$\begin{aligned} \text{SN40} = & f(\text{aggregate characteristics}) \\ & + f(\text{polishing action}) + f(\text{seasonal effects}) \end{aligned} \quad \text{Eqn. 2}$$

Empirical observations confirm that the polishing action of accumulated traffic does indeed cause skid resistance to decay from an initial value. The rate of skid resistance loss progressively diminishes and eventually skid resistance stabilizes at a lower level. This study considered only those pavements judged to have already reached their terminal skid values, effectively screening out the rate of skid loss from this analysis. Thus, Equation 2 simplifies to that of Equation 3 when specifically addressing later stage skid resistance measurements.

$$\text{SN40} = f(\text{aggregate characteristics}) + f(\text{seasonal effects}) \quad \text{Eqn. 3}$$

4.1 Minimum Polish Value

The first model considered was the simple relationship of a deteriorating microtexture with cumulative polishing over time. This relationship was sought for various aggregates through the use of an accelerated test procedure using the British Polishing Wheel and the British Pendulum Test. A graphical representation of this relationship is presented in Figure 2. The importance of this model cannot be overstated -- it is the nexus of this entire study. Subsequent

Aggregate microtexture (PV) approaches an asymptote with cumulative hours of polish

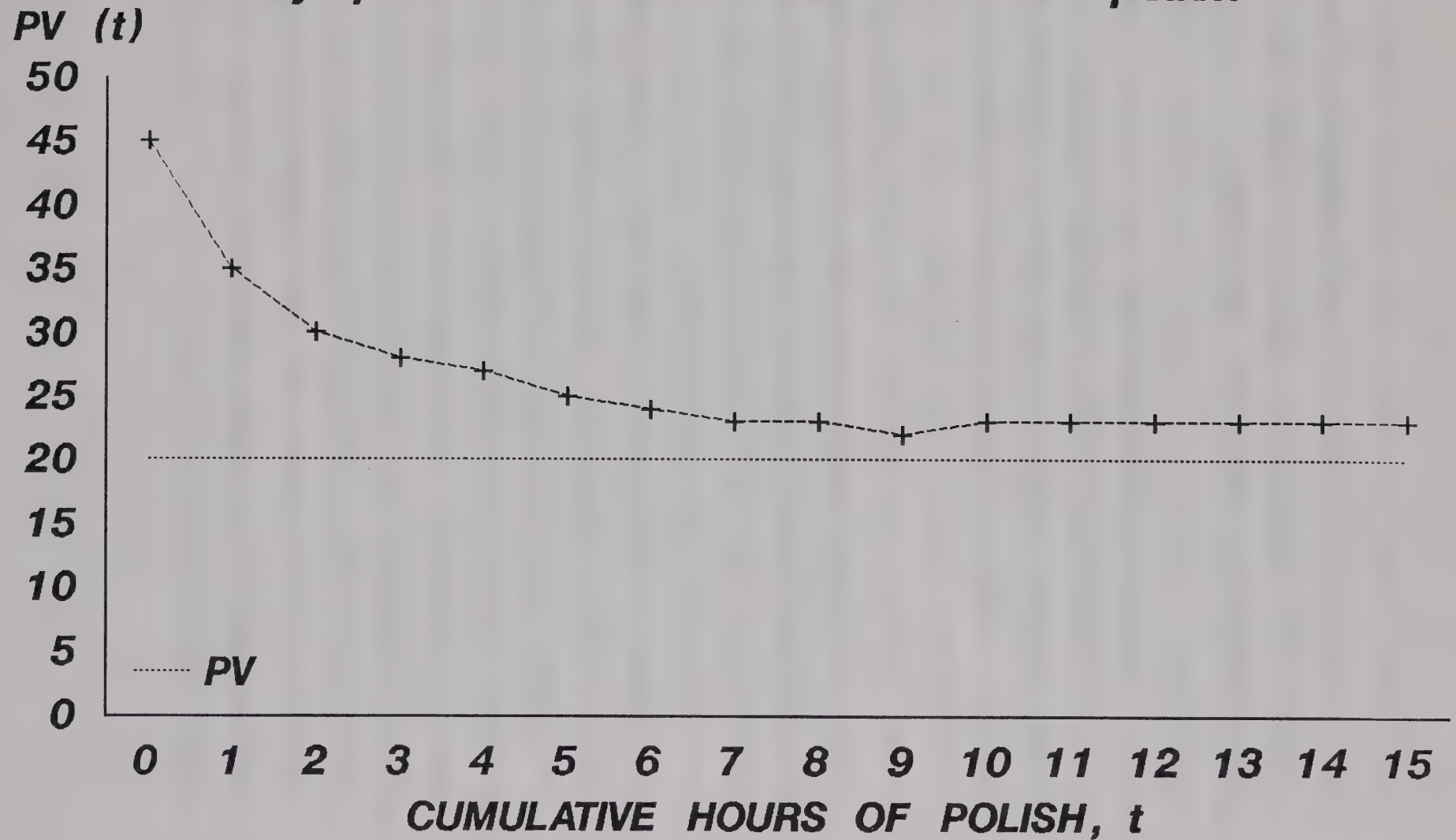


Figure 2

use of this model is based on the hypothesis that the estimated minimum polish value for each aggregate is somehow related to the terminal skid resistance actually observed when that aggregate is used in the mix design.

4.2 Terminal Skid Resistance

The minimum, terminal skid resistance value of a bituminous mix has historically been difficult to estimate despite a substantial amount of research suggesting various adjustments (4,5,6). In this study, the skid resistance value (SN40) measured with a standard ribbed tire (ASTM E-501) at 64 kph(40 mph) was selected to be the base measure. This test procedure corresponds to ASTM E-274 and was convenient to use because it is the standard used in New Jersey's skid resistance inventory program.

Based on earlier work in New Jersey, it was postulated that a horizontally level, cyclically varying value of skid resistance may be expected after approximately two million vehicle passes on bituminous pavements (7,8,9). After this amount of traffic, the pavement's skid resistance value is affected predominantly by day-to-day and seasonal effects as shown in Figure 1. Thus, it was hypothesized that a theoretical minimum stabilized skid resistance could be determined with an appropriate model as a function of environmental factors.

4.3 The Missing Link

The third hypothesis investigated is that an aggregate's minimum polish value is related to the terminal aggregate microtexture reached in the field. The hypothesis further assumes that this level of microtexture, together with a seasonal adjustment factor, **exclusively** determines the skid resistance of a pavement after a specific accumulation of traffic.

5.0 Experimental Scope

In order to test the theories presented in the last section, three separate experiments were conducted. The first experiment constitutes Phase 1 of this study -- determining the effect of accelerated laboratory polishing on aggregate microtexture. Phase 2 is composed of two separate experiments, designed to relate the minimum polish value of an aggregate to the terminal skid resistance value observed under field conditions. Because the relationships under test in this study were actually modular components of a larger model, it is important to note that the statistical information used to estimate one relationship was not reused in the estimate of another.

The first two experiments consisted of data collection and analysis, resulting in the development of two distinct

statistical models estimating the relationships between the various parameters. Additional data was then collected to determine the missing link, the ultimate correlation between the minimum polish value and the terminal value of skid resistance.

5.1 Phase 1: Laboratory Measurements of Microtexture

This phase of the study followed a five-step program; sampling, preparation of samples, accelerated polishing and pendulum testing, and data analysis.

5.1.1 Sampling

Aggregate samples of #57 and #67 stone were gathered at selected quarries in accordance with ASTM D75 and AASHTO T2. The aggregate samples were then assigned serial numbers for ease of reference; recording quarry sampled, date sampled, and type of aggregate. Each sample was then sieved to produce a sample composed of a specified size aggregate (passing 1/2 inch, retained on 3/8 sieve). The aggregate sample was then washed, dried and stored for future test specimen preparation.

5.1.2 Preparation of Test Specimens

Polishing wheel specimens were prepared in accordance with ASTM D3319 which entails the production of polyester

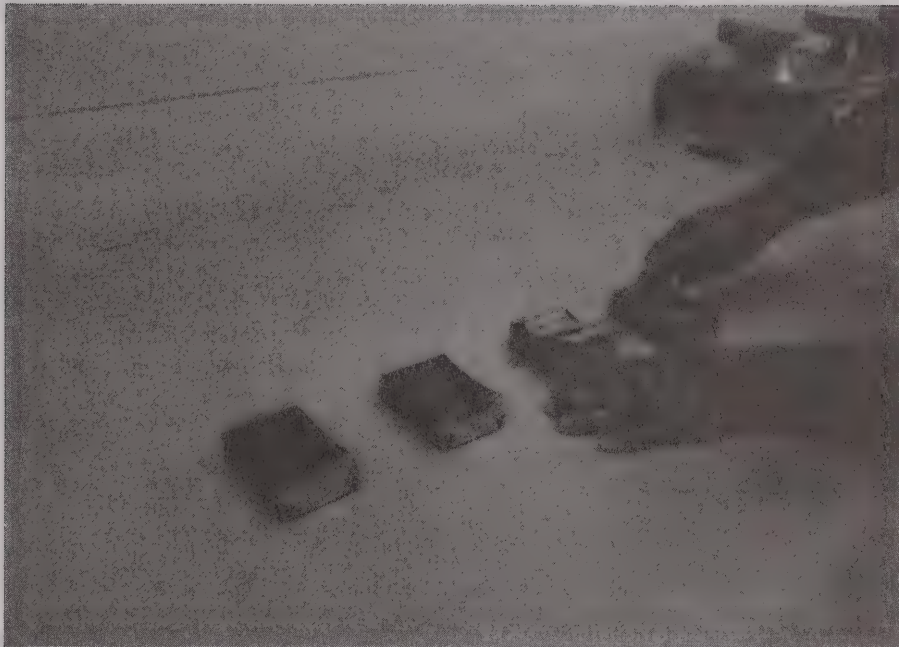


Figure 3: Preparation of polishing wheel test specimens

resin-aggregate molds, which fit around the periphery of the accelerated polishing wheel. The molds (see Figure 3) are precoated with silicon spray, then wiped clean, so as not to contaminate the aggregate. A single layer of dry aggregate is placed by hand into each mold, leaving as few gaps as possible between aggregates.

Polyester resin is then mixed according to the following formula :

Polyester resin	300 gram
Wollastonite (CaSiO_3)	90 gram
Aerosil (Colloidal Silica)	19 gram
6% Cobalt Naphthenate Solution	1.5 gram
MEK(OH) ₂ in Plasticizer	2.8 gram
Anhydrous glycerol	1.0 ml

This bonding agent is then spread over the aggregates, filling the mold. When the resin has cured properly (6-8 hrs), the specimen is stripped from the mold and the edges are dressed with a belt sander. Seven samples for each quarry were prepared in this manner. Two sets of seven samples were polished at one time.

5.1.3 Accelerated Polishing Test

The British Polishing Wheel, manufactured by Wessex Engineering and Metalcraft Co. of Somerset, England is designed to simulate the polishing action of vehicular tires under conditions similar to those occurring on the surface of the roadway. The polishing wheel induces a polishing action by

feeding a slurry of silicon carbide grit and water at the contact point between a hard solid rubber tire and the specimen wheel (see Figure 4). The specimen wheel rotates at a constant 320 rpm. The slurry is fed at a rate of 50 to 75 milliliters per minute with grit at 6-7 grams per minute. Specimens were removed from the polishing wheel at set intervals (1, 2, 4, 6, 8, 10 hrs, etc.) for testing with the British Pendulum Tester. Difficulty was encountered with specimen breakage so that often the full complement of seven samples was reduced to four or five.

5.1.4 British Pendulum Test

The British Pendulum Tester is a dynamic pendulum impact tester which measures the energy loss when a rubber slider edge is propelled by gravity over the aggregate test specimen (see Figure 5). The values measured in the laboratory after t hours of polishing, $PV(t)$, is a relative number which relates to the skid resistance of the exposed aggregates in a roadway surface at a given point in time.

After removal from the polishing wheel, each test specimen is cleaned of all grit, then locked into the specimen base. The pendulum tester is leveled and zeroed, the height of the pendulum is adjusted so as to impact the same area of the test specimen at each test, and a thin film of water is applied to the specimen. The pendulum is then

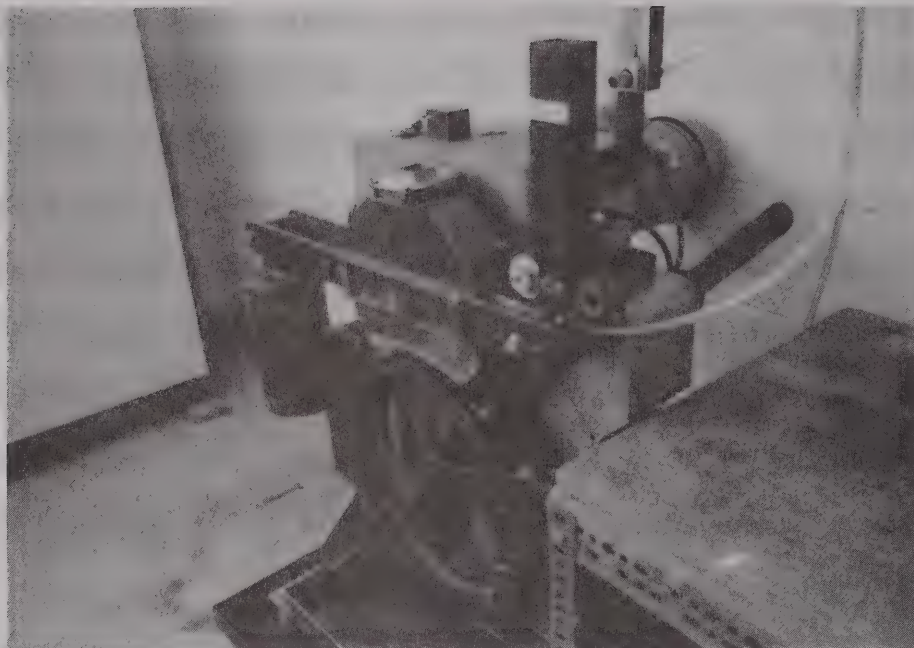


Figure 4: The British Polishing Wheel

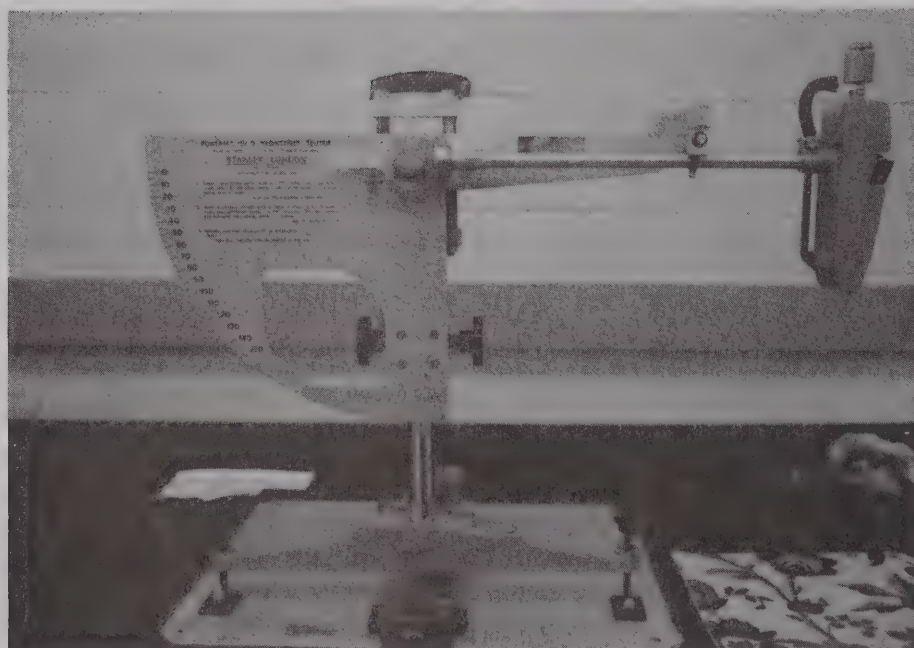


Figure 5: The British Pendulum Tester

released. The value obtained from the first swing is not recorded, so as to allow the slider to self-adjust to the surface of the specimen. Five swings are then made, and their values recorded with the hours of polishing.

5.1.5 Data Analysis

The average of the five pendulum swings were calculated and the average of the seven samples were calculated. This value is designated as the $PV(t)$ where t equals the hours of polishing. Originally, the samples were polished and tested at two-hour intervals until the polishing curve appeared to level off. Midway through collection of data, repeatability tests indicated that $PV(t)$ s were precise to within a standard deviation of approximately 0.50 units. On the basis of this, a decision rule was developed that the samples would be polished and tested at two-hour intervals for ten hours, after which testing would continue until the difference between three successive average readings was less than or equal to 0.5 units. Since samples from two quarries were polished at the same time, the test was continued until both met this criteria. These data were then used as input to various regression models.

5.2 Phase 2: Field Measurements of Seasonal Effects

For this experiment, five old, well-polished bituminous

pavements (AADT ranging from 20,000 to 40,000), each with cumulative traffic in excess of two million passes, were selected as field test locations. The five locations represented three aggregate types and produced skid resistance measurements ranging from approximately 25 to 45 SN40 units. These sites were selected not for their statistical variability or appropriateness, but rather for their close proximity to research and skid test offices to provide the maximum testing schedule. Field measurements of skid resistance, macrotexture (sand patch method), microtexture (BPN), date, and daily weather conditions were made at two-week intervals (weather permitting) over a one-year period. These measurements and the approximate cumulative traffic were reported to the data base. Cumulative traffic was estimated from AADT inventory information and number of traffic lanes.

5.3 Phase 2: Measurements to Identify the Missing Link

In order to collect paired data sets of minimum polish value and terminal skid resistance values, an additional series of skid test sites were chosen which spanned the range of skid resistance levels across New Jersey; SN40s from 25 to 50. Twenty-six bituminous pavements were identified (AADT ranging from 5000 to 80,000) which, by virtue of each having sustained a minimum of four million vehicle passes, were

concluded to have reached their terminal levels of skid resistance.

Each location was skid tested and subsequently cored. Skid test measurements were made at 40 mph wherever possible, or adjusted to 40 mph using an in-house correction. The average of three separate passes over each core site determined the average skid number for the site. The date of skid test and ambient air temperatures were noted. Additional weather data for each site was taken from National Weather Service data at local recording stations.

The cores were then mildly heated in the laboratory and the internal (unpolished) surface course aggregates were separated, cleaned and sieved to the sample requirements of ASTM D-3319. The surface aggregates--those which had already been polished by traffic--were not used in the test.

Polishing wheel specimens were then manufactured with the "virgin" aggregates. The specimens were polished in the laboratory and their loss in microtexture measured with the British Pendulum Tester.

6.0 Results

Tables 1, 2 and 3 present the data collected for each of the three experiments described above. Table 1 shows the change in $PV(t)$ with hours of accelerated polishing for samples from twenty-seven quarries. The data is segregated

TABLE 1
PV(t) VALUES FOR QUARRY SAMPLES

CRUSHED GRAVEL								TRAPROCKS									
hrs	161	C	160	160	160	161	161	hrs	53	258	248	220	53	170	29	69	258
0.0	48.4	48.3	47.8	47.9	46.5	45.3	43.4	0.0	47.6	48.8	44.3	49.0	45.6	44.7	45.2	44.5	38.3
1.0	42.7	45.0	40.3	41.5	40.2	38.1	37.9	1.0	40.0	39.8	38.6	37.4	36.4	36.5	35.6	34.7	33.6
2.0	43.3	44.0	39.3	42.5	38.2	36.9	36.3	2.0	40.0	38.6	35.5	36.4	35.2	37.2	35.0	32.3	32.1
4.0	41.3	41.3	37.5	40.8	36.5	35.6	34.3	4.0	39.5	35.4	35.3	34.6	33.5	32.8	32.8	30.8	30.3
6.0	40.8	39.5	36.8	38.5	35.5	33.9	32.4	6.0	38.0	34.9	34.8	33.5	32.5	36.2	30.4	31.0	29.6
8.0	38.5	40.8	35.8	37.0	36.6	34.3	33.1	8.0	36.8	34.8	32.7	33.9	32.4	31.0	30.2	28.0	28.4
10.0	39.0	36.8	36.5	35.5	34.8	33.1	31.9	10.0	35.0	34.3	32.5	32.2	31.8	31.7	29.4	27.3	27.1
12.0	37.7			38.8	34.3	32.9	31.6	12.0			31.8		31.3	30.7		26.3	26.1
14.0	36.8			35.5	33.3	31.3	31.6	14.0			31.0		30.5	30.5		26.3	27.1
16.0	37.1			33.3	32.1	31.1		16.0			31.0		31.0	28.7		26.8	
18.0	36.2			34.3		31.3		18.0			29.2		31.9	29.3			
20.0				34.5				20.0			28.2						
22.0				33.8				22.0									
24.0								24.0									

ARGILLITES									CARBONATE ROCKS								
hrs	280	184	151	48	184	142	214	142	hrs	192	127	174	282	281	188	173	84
0.0	45.4	44.6	45.0	46.0	45.5	45.0	44.9	41.8	0.0	45.2	43.7	47.6	47.3	46.7	43.2	42.2	41.6
1.0	39.6	36.1	34.9	36.7	36.4	36.2	33.9	31.7	1.0	36.3	32.5	32.9	32.6	32.7	28.4	30.0	30.4
2.0	40.0	33.1	32.3	36.9	35.1	35.5	33.1	31.2	2.0	32.7	30.2	29.2	30.8	28.7	23.8	26.3	26.4
4.0	40.3	33.3	31.6	34.0	33.1	35.0	32.1	28.7	4.0	33.2	30.4	27.4	30.1	26.6	25.7	23.8	22.3
6.0	39.5	35.4	30.2	34.4	32.8	34.0	31.4	27.2	6.0	33.2	29.5	25.6	27.4	24.6	25.5	23.3	23.8
8.0	38.2	33.4	32.6	32.3	32.2	33.5	30.7	27.1	8.0	36.8	28.0	24.4	27.6	24.7	24.4	22.2	21.4
10.0	38.5	35.0	33.6	33.2	32.9	31.5	30.0	28.5	10.0	34.4	29.0	25.7	24.0	23.4	22.3	20.4	20.2
12.0	39.0	33.0	29.6	33.0	34.0		30.0	29.2	12.0	31.6		25.0	22.4	22.5	21.3	21.1	20.7
14.0	38.2	27.3	29.2	32.5			29.8	26.7	14.0	32.2			23.8	22.1	20.9		
16.0	38.2		27.8	32.8				26.7	16.0	30.6			23.6	21.8			
18.0	37.8		26.4	32.0				29.0	18.0	30.0			23.6	21.6			
20.0			26.2						20.0	29.8							
22.0			26.0						22.0	30.4							
24.0			25.2						24.0	29.6							

GNEISS

hrs	73	202	60	166	131
0.0	50.8	48.8	44.0	45.3	45.4
1.0	45.0	44.7	34.2	34.3	34.9
2.0	41.2	37.2	33.6	35.2	31.9
4.0	39.3	34.6	31.4	32.8	31.1
6.0	37.6	33.1	29.8	31.4	31.2
8.0	37.1	32.5	29.4	28.0	29.4
10.0	37.4	33.0	29.0	29.0	28.4
12.0	34.9	31.5	29.8	30.0	30.4
14.0	35.5	32.0	29.6	29.4	29.2
16.0	35.7	32.7	28.6	27.4	29.2
18.0	33.8	31.3	28.2	27.0	28.0
20.0	34.5	29.8	28.6	27.8	28.4
22.0				27.8	

TABLE 2

DATA USED TO MODEL ENVIRONMENTAL INFLUENCE ON SN40

SITE	JDAY	SN40	BPN	MACRO		CUM. DRY SPELL		SITE	JDAY	SN40	BPN	MACRO		CUM. DRY SPELL	
				TEXTURE	TEMP	TRAFFIC FACTOR						TEXTURE	TEMP	TRAFFIC FACTOR	
				(cm) *	(deg C)	(million	**					(cm) *	(deg C)	(million	**
001	205	38	55.5	0.0848	28.5	22.4	1.79	004	205	38	50.7	0.0897	28.5	15.9	1.79
	223	43	55.3	0.0767	22.8	22.6	0.00		223	38	51.9	0.0879	22.8	16.0	0.00
	234	41	55.1	0.0678	21.0	22.7	0.00		234	39	52.8	0.0986	21.0	16.1	0.00
	248	41	54.3	0.0818	21.0	22.8	1.95		248	39	54.6	0.0838	21.0	16.2	1.95
	261	42	58.5	0.0767	20.0	22.9	0.00		261	38	52.3	0.1054	20.0	16.2	0.00
	275	40	57.7	0.0772	20.0	23.0	0.00		275	38	53.4	0.0861	20.0	16.3	0.00
	290	44	57.9	0.0790	15.6	23.2	1.10		290	39	55.1	0.0792	15.6	16.4	1.10
	329	45	----	-----	7.2	23.6	0.00		329	40	----	-----	7.2	16.6	0.00
	6	43	66.9	0.0749	-1.7	23.9	1.40		6	39	68.6	0.0925	-1.7	16.8	1.40
	125	49	60.5	0.0828	16.0	25.1	0.00		125	45	57.9	0.1074	16.0	17.4	0.00
	141	46	----	-----	18.0	25.2	0.00		141	41	----	-----	18.0	17.5	0.00
	161	45	----	-----	21.1	25.4	0.00		161	45	----	-----	21.1	17.6	0.00
	188	45	----	-----	29.0	25.6	----		188	43	----	-----	29.0	17.8	----
002	205	40	54.7	0.0947	28.5	22.4	1.79	005	205	49	64.2	0.1311	28.5	14.9	1.79
	223	41	53.1	0.1229	22.8	22.6	0.00		223	53	62.9	0.1090	22.8	15.0	0.00
	234	41	56.4	0.0973	21.0	22.7	0.00		234	52	61.7	0.0757	21.0	15.0	0.00
	248	41	54.0	0.0828	21.0	22.8	1.95		248	51	62.8	0.1074	21.0	15.0	1.95
	261	42	56.2	0.1069	20.0	22.9	0.00		261	50	62.5	0.1092	20.0	15.1	0.00
	275	41	55.7	0.0914	20.0	23.0	0.00		275	47	66.3	0.1080	20.0	15.1	0.00
	290	43	58.1	0.0841	15.6	23.2	1.10		290	52	67.6	0.0932	15.6	15.2	1.10
	329	43	----	-----	7.2	23.6	0.00		329	50	----	-----	7.2	15.3	0.00
	6	43	69.9	0.0810	-1.7	23.9	1.40		6	52	73.0	0.1034	-1.7	15.4	1.40
	125	47	64.2	0.0932	16.0	25.1	0.00		125	55	67.1	0.1146	16.0	15.8	0.00
	141	47	----	-----	18.0	25.2	0.00		141	52	----	-----	18.0	15.9	0.00
	161	47	----	-----	21.1	25.4	0.00		161	51	----	-----	21.1	15.9	0.00
	188	46	----	-----	29.0	25.6	----		188	55	----	-----	29.0	16.0	----
* Modified sandpatch method ** Dry spell factor = ln (days since last rain > 0.1 in. + 1)															
003	205	27	46.3	0.0792	28.5	15.9	1.79								
	223	28	46.0	0.0795	22.8	16.0	0.00								
	234	31	45.4	0.0836	21.0	16.1	0.00								
	248	33	45.3	0.0729	21.0	16.2	1.95								
	261	32	45.8	0.0864	20.0	16.2	0.00								
	275	31	50.3	0.0780	20.0	16.3	0.00								
	290	33	50.1	0.0439	15.6	16.4	1.10								
	329	32	----	-----	7.2	16.6	0.00								
	6	32	59.7	0.0625	-1.7	16.8	1.40								
	125	32	50.3	0.0668	16.0	17.4	0.00								
	141	33	----	-----	18.0	17.5	0.00								
	161	32	----	-----	21.1	17.6	0.00								
	188	36	----	-----	29.0	17.8	----								

TABLE 3

DATA SET USED TO DEVELOP CORRELATION BETWEEN
MINIMUM POLISH VALUE AND TERMINAL SKID NUMBER

SITE*	JULIAN DATE	MEASURED SN40	MINIMUM POLISH VALUE
R1	153	32.8	34.1
R2	153	46.7	29.0
R3	153	50.1	34.0
R4	149	40.2	31.3
R5	149	22.2	23.8
R6	149	37.2	33.5
R7	149	28.7	29.5
R8	149	27.3	30.3
R9	154	29.1	23.6
R10	154	26.3	27.1
R11	154	51.1	26.8
R12	154	50.8	30.4
R13	153	47.4	29.9
R14	148	53.9	28.2
R15	154	44.8	29.2
R16	148	42.3	32.1
R17	148	46.4	32.8
R18	148	51.3	30.2
R19	148	49.8	32.7
R20	147	50.6	30.3
R21	147	46.0	31.7
R22	147	41.8	28.0
R23	143	46.8	29.3
R24	143	49.8	31.2
R25	142	31.0	24.7
R26	142	40.3	27.8

* Ri indicates one of the 26 research
test sites in the study.

into five categories, indicating the five aggregate types under study; carbonate rock, argillite, gneiss, traprock and crushed gravel.

Table 2 shows the data set used to analyze the seasonal and environmental influence on skid resistance for the five test locations chosen. Data was sought at two-week intervals throughout the year -- the date of test is indicated in julian calendar days, while the field data collected is shown as skid number at 40 mph(SN40), British Pendulum Number(BPN), macrotexture, temperature, cumulative traffic and dry spell factor. The dry spell factor is a function of rainfall, equal to the natural logarithm of one plus the number of days since the last rainfall of greater than 0.1 inch. Rainfalls which occurred more than seven days before the date of test were neglected.

Table 3 shows the estimated minimum polish values for the twenty-six aggregate samples obtained from cored pavements, their corresponding skid number at 40 mph and the julian calendar date. These are the parameters investigated in the subsequent analysis.

7.0 Phase 1: Analysis of Findings

Examination of the test data (see Figure 6) suggested that an exponential model and a transformed linear model should be examined in order to establish the form which best

*Typical Plot of Raw Polish Data
(Gneiss Aggregates)*

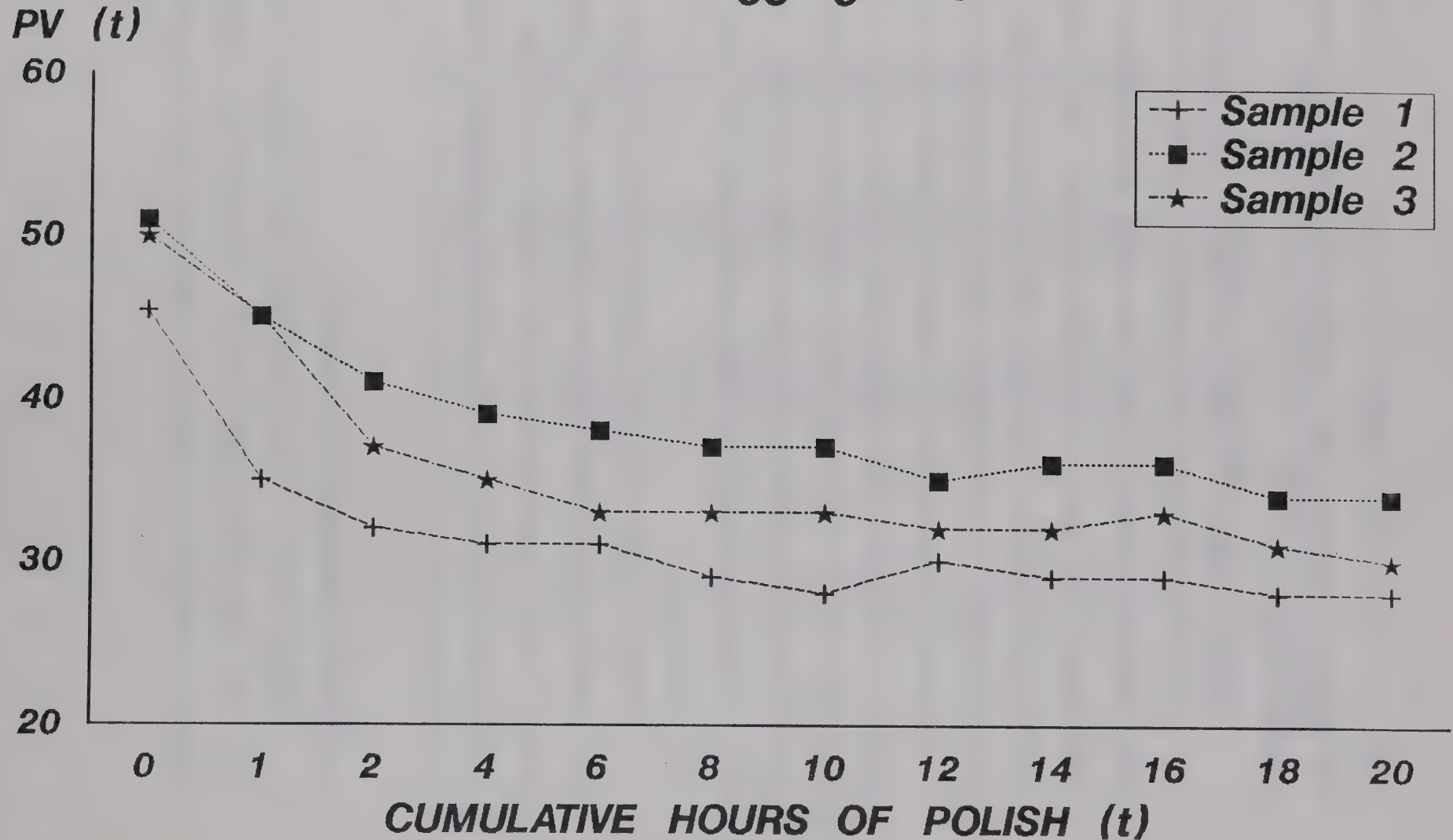


Figure 6

describes the relationship between polish value ($PV(t)$) and hours of polishing(t). Each model examined describes a function which at $t = 0$, $PV(t)$ equals the intercept (the unpolished value) and as t becomes infinitely large, $PV(t)$ becomes asymptotic to the minimum polish value, PV .

Analyses of the data were undertaken, using the Statistical Analysis System's (SAS) linear regression (GLM) and non-linear regression (NLIN) procedures. After a number of models were tested, two were found to be the best, having the greatest correlation coefficient and/or least sum of the squared residuals.

7.1 Model I

Model I was developed as a linear regression of $PV(t)$ versus a simple transformation of the variable, t . Transformation of a variable to its inverse is a common regression analysis technique. In this case, in order to avoid dividing by zero, 1 is added to t , so that when $t = 0$, $1/(t+1) = 1$.

$$\text{Model I: } PV(t) = PV_1 + a_1(1/(t+1)) \quad \text{Eqn. 4}$$

Application of this generalized model to each of the aggregates shows good correlation. As shown in Table 4, the correlation coefficient for each aggregate source is high, on the average, greater than 0.90. The value for the constant,

TABLE 4

MODEL I: $PV(t) = PV + a1(1/t+1)$

SAMPLE	PV	a1	R-SQUARED
CR1	24.0	20.7	0.97
CR1	20.2	31.3	0.91
CR3	19.1	22.8	0.99
CR4	19.1	22.5	0.99
GN1	27.5	17.8	0.93
GN2	27.9	15.6	0.98
GN3	27.7	16.8	0.96
GN4	34.7	17.4	0.95
GN5	30.6	20.0	0.93
TR1	30.3	14.8	0.98
TR2	25.9	18.7	0.97
TR3	31.3	13.6	0.95
TR4	30.3	16.4	0.96
TR5	29.9	15.2	0.86
TR6	29.7	16.9	0.98
TR7	26.9	12.3	0.93
ARG1	29.1	13.4	0.93
ARG2	31.6	13.8	0.96
ARG3	30.1	14.3	0.86
ARG4	35.9	8.9	0.96
ARG5	28.5	15.3	0.96
CG1	34.8	12.6	0.99
CG2	35.0	14.1	0.81
CG3	34.0	13.1	0.91
CG4	32.7	13.8	0.94
CG5	34.4	16.2	0.90
CG6	38.6	10.7	0.83

PV_1 , representing the asymptote of the curve, indicates that aggregates of the same geologic type have similar minimum polish values. Figure 7 shows typical Model I polish curves for gneiss.

7.2 Model II

Model II represents a more conventional (exponential) form for data of this type. This model required the use of non-linear regression techniques on the equation:

$$\begin{array}{lll} \text{Model II:} & A_2 t & \\ PV(t) = PV + A_1 (e^{-A_2 t}) & A_2 < 0 & \text{Eqn. 5} \end{array}$$

The SAS non-linear regression procedure requires that estimates be made for each of the constants, PV , A_1 , and A_2 . In this model, PV represents the value of the minimum polish value, A_1 represents the difference between the maximum and minimum $PV(t)$ value, and A_2 represents the rate of decline of $PV(t)$ versus t . The SAS program modifies each constant by small increments, testing the sum of the squared residuals (the difference between the observed and predicted values) for a minimum value. Correlation coefficients are not available in this type of analysis, so it is more difficult to analyze. In this analysis, the sum of the squared residuals were compared with those of other models. Model II represents the best exponential form for these data. The similarity between the asymptote, PV , for each aggregate type is no-

Typical Model I Polish Curves (Gneiss Aggregates)

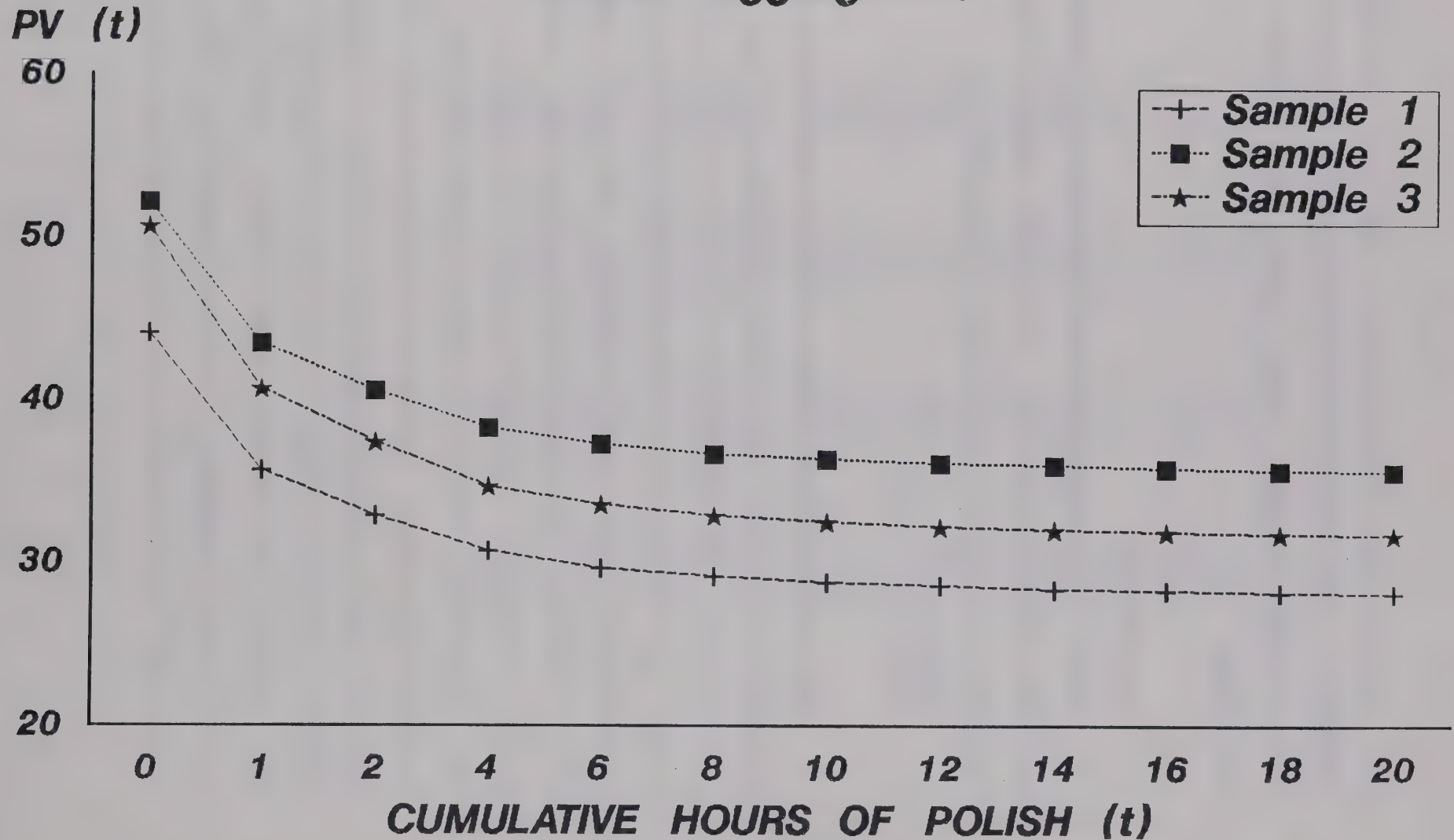


Figure 7

ticeable, as shown in Table 5. Figure 8 shows typical Model II polish curves for gneiss.

7.3 Comparison of Models

Two techniques were employed to compare Models I and II in order to determine which model best describes the data for each aggregate type. The first technique used compares the sum of the squared residuals from each model. In order to make a comparison, the data was manipulated so that for each aggregate type, a constant sample size was chosen. The results of this comparison is shown in Table 6. On the average, there is no significant difference between the two models.

The second technique used was to determine the 95 percent upper and lower confidence limits about the asymptote given for each of the two models. The model with the narrowest confidence limit band (within two standard deviations) would seem to be that which is more accurate to use for values of $PV(t)$ when t is infinitely large; i.e. the "true" minimum polish value, PV . These results are presented in Table 7.

The results shown in Table 7 indicate that Model II more accurately defines the PV for each aggregate source.

7.4 Selection of Model

The appropriate model form for the laboratory-measured

TABLE 5

$$\text{MODEL II: } PV(t) = PV + A1(e^{A2t})$$

SAMPLE	PV	A1	A2	SUM OF SQUARED
				RESIDUALS
CR1	26.9	18.7	-1.1	8.5
CR2	23.3	19.0	-1.4	22.7
CR3	21.8	20.2	-0.8	5.8
CR4	21.6	19.7	-0.7	8.6
GN1	28.5	15.1	-0.5	32.9
GN2	29.2	14.3	-0.8	9.5
GN3	29.4	15.9	-1.0	10.3
GN4	35.3	14.8	-0.4	10.5
GN5	31.7	17.6	-0.4	12.4
TR1	31.8	13.5	-0.8	7.2
TR2	27.4	16.1	-0.6	20.7
TR3	32.0	11.4	-0.4	10.9
TR4	31.7	14.5	-0.6	12.4
TR5	30.0	12.6	-0.3	33.9
TR6	32.1	14.7	-0.9	7.0
TR7	26.8	10.7	-0.3	4.8
ARG1	30.6	12.6	-1.0	10.3
ARG2	33.0	12.6	-0.9	9.5
ARG3	31.9	13.0	-1.0	27.0
ARG4	36.7	7.8	-0.6	3.9
ARG5	30.9	13.9	-1.3	5.6
CG1	36.6	11.0	-0.9	2.5
CG2	33.8	12.1	-0.2	24.6
CG3	35.2	11.4	-0.6	18.5
CG4	33.5	11.7	-0.4	12.2
CG5	36.7	15.4	-1.3	9.9
CG6	37.0	10.8	-0.2	6.6

Typical Model II Polish Curves (Gneiss Aggregates)

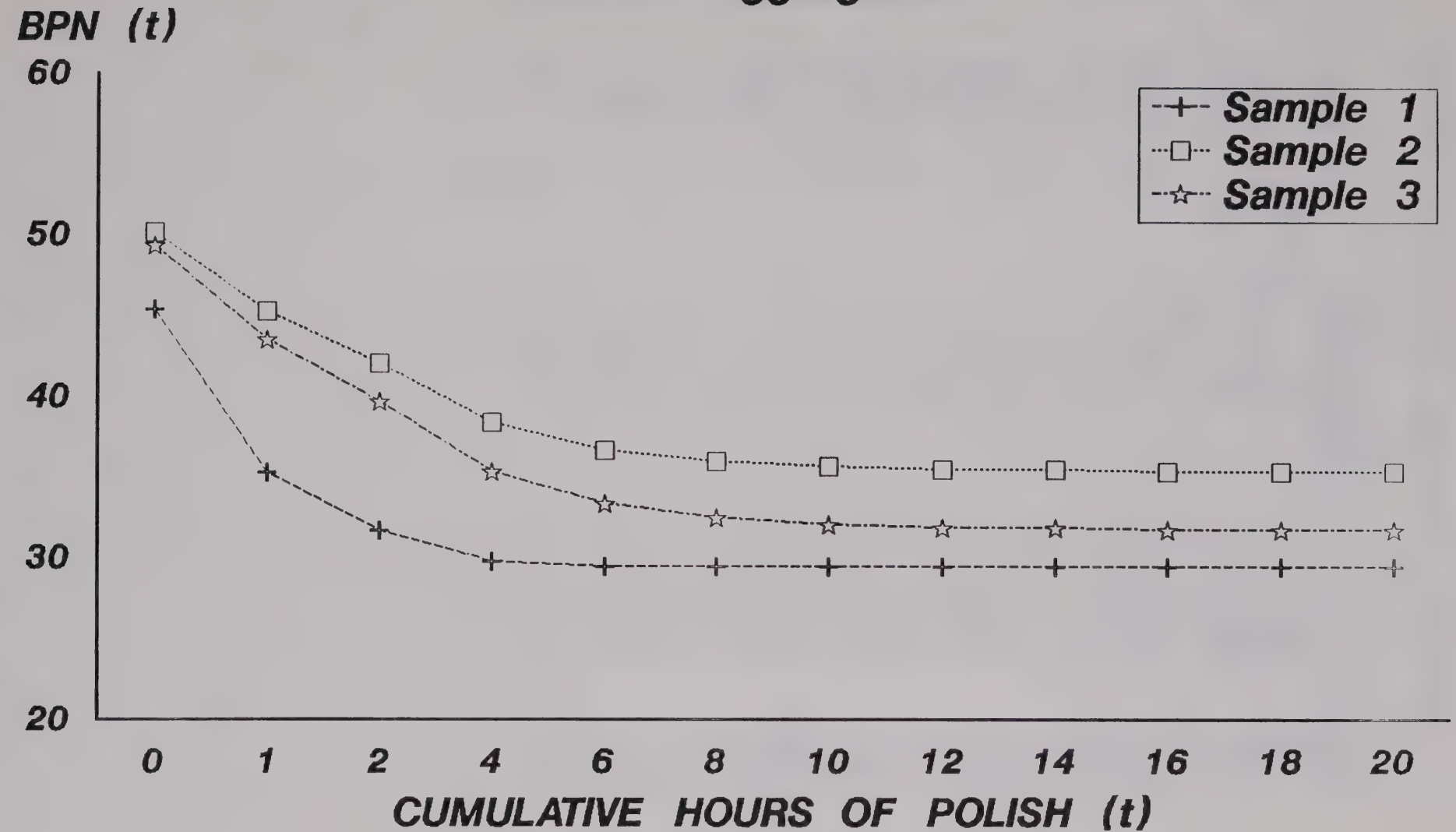


Figure 8

TABLE 6

COMPARISON OF MODELS: SUM OF SQUARED RESIDUALS

SAMPLE	n	MODEL I: SUM OF SQD RESIDUALS	MODEL II: SUM OF SQD RESIDUALS
CR1	12.0	8.5	8.5
CR2	12.0	31.4	16.1
CR3	12.0	2.5	5.8
CR4	12.0	3.2	8.6
GN1	20.0	20.1	32.3
GN2	20.0	4.4	9.5
GN3	20.0	8.9	10.3
GN4	20.0	13.4	10.5
GN5	20.0	25.1	12.4
TR1	14.0	2.8	7.2
TR2	14.0	9.3	18.9
TR3	14.0	6.4	9.5
TR4	14.0	8.0	12.2
TR5	14.0	21.6	27.2
TR6	10.0	8.4	4.8
TR7	14.0	3.9	7.0
ARG1	12.0	6.9	4.9
ARG2	12.0	5.8	7.4
ARG3	12.0	7.0	1.0
ARG4	12.0	2.3	3.9
ARG5	12.0	7.6	5.6
CG1	10.0	1.4	2.5
CG2	16.0	31.8	24.0
CG3	16.0	13.2	18.5
CG4	16.0	9.1	12.2
CG5	14.0	21.9	9.9
CG6	10.0	14.9	6.6

TABLE 7

COMPARISON OF MODELS: MINIMUM POLISH VALUE RANGES

SAMPLE	MODEL I:		MODEL II:	
	PV AT 95% CONFIDENCE	RANGE	PV AT 95% CONFIDENCE	RANGE
CR1	21.0-27.5	6.50	25.4-28.5	3.10
CR2	14.8-26.0	11.20	21.3-25.2	3.90
CR3	17.6-21.1	3.50	20.5-23.2	2.70
CR4	17.3-21.4	4.10	19.9-23.3	3.40
GN1	24.5-30.8	6.30	27.0-30.0	3.00
GN2	26.4-29.6	3.20	28.5-30.1	1.60
GN3	25.6-30.1	4.50	28.6-30.2	1.60
GN4	32.1-37.6	5.50	34.3-36.4	2.10
GN5	27.1-34.6	7.50	30.6-32.7	2.10
TR1	28.9-32.0	3.10	30.9-32.6	1.70
TR2	23.6-28.6	5.00	25.9-28.9	3.00
TR3	28.9-33.8	4.90	30.5-33.4	2.90
TR4	27.9-32.9	5.00	30.4-33.0	2.60
TR5	25.6-34.5	8.90	27.2-32.8	5.60
TR6	-----	-----	30.2-34.1	4.00
TR7	24.1-29.8	5.70	25.2-28.5	3.30
ARG1	26.5-31.9	5.40	29.6-31.5	1.90
ARG2	29.7-33.7	4.00	32.1-33.9	1.80
ARG3	25.4-35.1	9.70	29.7-34.1	4.40
ARG4	34.3-37.7	3.40	35.5-38.0	2.50
ARG5	25.6-31.8	6.20	29.7-32.1	2.40
CG1	33.4-36.5	3.10	35.4-37.8	2.40
CG2	30.6-39.7	9.10	31.1-36.6	5.50
CG3	30.9-37.4	6.50	33.6-36.9	3.30
CG4	30.2-35.5	5.30	32.0-35.0	3.00
CG5	30.0-39.1	9.10	35.4-37.9	2.50
CG6	33.6-43.8	10.20	30.1-43.9	13.80

microtexture decay rate has been presented in Figure 2; where it can be seen that the microtexture progressively becomes smoother and approaches an asymptotic value. This asymptote is referred to as the minimum polish value (PV) associated with a specific aggregate. This asymptotic trend was clearly displayed by all of the 27 aggregates tested.

A mathematical expression describing this form of a model is given by Equation 5.

$$PV(t) = PV + A_1(e^{A_2 t}) \quad A_2 < 0 \quad \text{Eqn. 5}$$

where $PV(t)$ = laboratory measured microtexture after
t hours of polishing

PV = asymptotic minimum polish value

A_1, A_2 = estimated parameters controlling loss
in microtexture over hours polished.

This model was highly successful in representing the observed data trends. The estimated minimum PV values were precise to within, typically, ± 2 units at the 95 % level of confidence. The estimated minimum PV values ranged from 21.6 to 37.0, as shown in Table 8, and confirmed that this test procedure was sensitive to the varying degrees of microtexture encountered in the sampled aggregates. Additionally, a good correlation was found between the rank order of the minimum PV estimates for the aggregates tested and

TABLE 8

MINIMUM POLISH VALUES DETERMINED FOR 27 AGGREGATE SAMPLES

SAMPLE*	HOURS POLISHED	ESTIMATED MINIMUM POLISH VALUE	95% CONFIDENCE INTERVAL FOR ESTIMATED MINIMUM POLISH VALUE	

CR1	12	26.9	25.4	TO 28.5
CR2	14	23.3	21.3	TO 25.2
CR3	12	21.8	20.5	TO 23.2
CR4	12	21.6	19.9	TO 23.3
GN1	22	28.5	27.0	TO 30.0
GN2	20	29.2	28.5	TO 30.1
GN3	20	29.4	28.6	TO 30.2
GN4	20	35.3	34.3	TO 36.4
GN5	20	31.7	30.6	TO 32.7
TR1	18	31.8	30.9	TO 32.6
TR2	18	27.4	25.9	TO 28.9
TR3	16	32.0	30.5	TO 33.4
TR4	16	31.7	30.4	TO 33.0
TR5	18	30.0	27.2	TO 32.8
TR6	10	32.1	30.1	TO 34.1
TR7	14	26.8	25.2	TO 28.5
ARG1	18	30.6	29.6	TO 31.5
ARG2	18	33.0	32.1	TO 33.9
ARG3	14	31.9	29.7	TO 34.1
ARG4	12	36.7	35.5	TO 38.0
ARG5	12	30.9	29.7	TO 32.1
CG1	10	36.6	35.4	TO 37.8
CG2	22	33.8	33.1	TO 36.6
CG3	16	35.2	33.6	TO 36.9
CG4	16	33.5	32.0	TO 35.0
CG5	12	36.7	35.4	TO 37.9
CG6	10	37.0	30.1	TO 43.9

* CRi indicates a carbonate rock quarry source
 Gni indicates a gneiss quarry source
 TRi indicates a traprock quarry source
 ARGi indicates an argillite quarry source
 CGi indicates a crushed gravel quarry source

the rank order of historical skid resistance data for similar aggregates in well-worn pavements. Thus it was concluded that the PV parameter was a good indicator of an aggregate's skid resistance potential.

Based on these findings, the asymptote estimation capabilities of the nonlinear regression model of Equation 5 was adopted for subsequent use in this study.

8.0 Phase 2: Analysis of Findings

8.1 Modeling Seasonal Variation in Skid Resistance

Several analyses were performed on the data collected for the determination of a seasonal adjustment of skid resistance. A direct multiple regression equation was found to predict skid resistance from field-measured microtexture (BPN), average daily temperature, and dry-spell factor ($R^2 = 0.83$). However, the utility of this particular relationship is limited. That is, it is much more practical to measure skid number directly, rather than require the labor-intensive task of measuring microtexture in the field. Therefore, the multiple regression approach was abandoned in favor of the following nonlinear regression analysis.

First, the observation was made that the temperature and dry-spell factors are inherently related to seasonal trends. Further investigation revealed that the field-measured BPN values were also seasonally influenced. Thus all of the

independent variables of the linear model above were linked to the julian calendar day, JDAY. A plot of SN40 versus JDAY demonstrated a distinct, cyclical pattern, as shown in Figure 9.

The value indicated as SN_{terminal} in Figure 9 represents that elusive value which we have been seeking, the terminal value of skid resistance for a well-polished pavement. To describe the cyclical pattern observed for skid resistance over time, a sine wave function was applied. The sine wave model adopted for use here is a simple function expressed as:

$$SN40 = SN_{\text{terminal}} + B_1 \sin(B_2 JDAY + B_3) \quad \text{Eqn. 6}$$

where $SN40$ = skid number measured at 64kph (40 mph)

JDAY = Julian calendar day

SN_{terminal} = terminal value of skid resistance

B_2 = a constant, (360/365), synchronizing
annual seasonal cycle to 360 degrees

B_1, B_3 = estimated regression coefficients

As shown in Figure 9, the lateral displacement of the cyclical wave is controlled by B_3 and the wave's amplitude by B_1 . The wave's elevation is controlled by SN_{terminal} .

The model described in Equation 6 was applied to the data collected on the five, well-polished pavements described in section 4.2. This indicated that in any particular geographic location, the timing of the seasonal effects, B_3 ,

SN40 versus JDAY for SITE 002
(Raw skid data in the form of a sine wave)

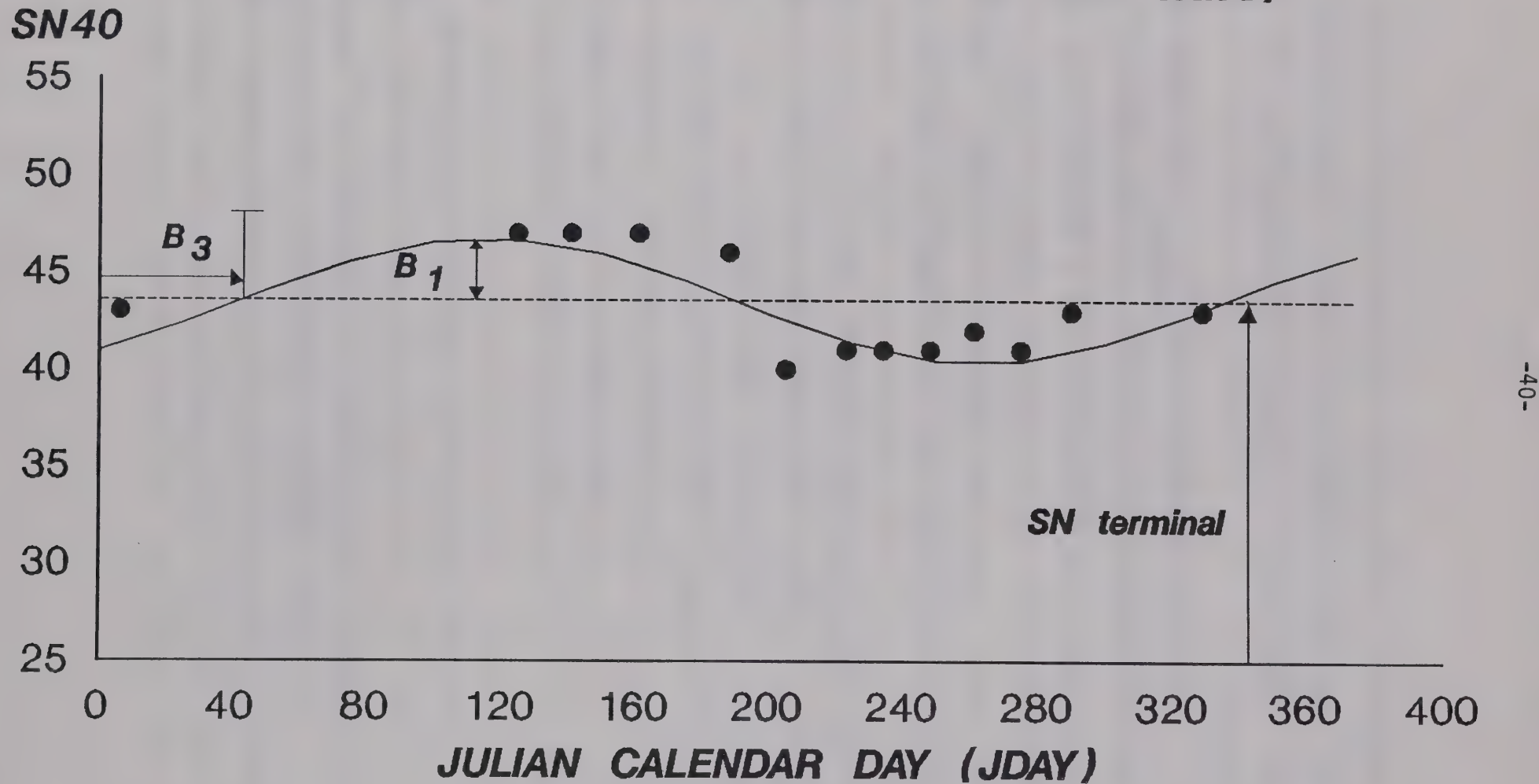


Figure 9

should be relatively constant. However, the degree to which these effects influence skid resistance, B_1 , may vary with each pavement. So, B_1 was estimated separately for each of the five pavements, while B_3 was ultimately assumed constant.

A very good fit was obtained for this model. The residual error is estimated to be approximately 1.9 SN40 units. The amplitude of the seasonal effect (B_1) was observed to range from approximately 1.3 to 3.3, depending upon the particular pavement. The lateral displacement of the seasonal effect (B_3) was estimated to be approximately 2 degrees (the equivalent of 2 days).

The model may be simplified with a negligible loss in precision if B_3 is set to zero. An additional simplifying assumption was made that the amplitude of the seasonal adjustment would also be held constant at a conservative (high) value. This would permit universal use of the seasonal adjustment model without attempting to calibrate it for each aggregate. Therefore, this analysis concluded with the adoption of the following model to estimate seasonal effects on SN40.

$$SN40 = SN_{terminal} + 3.0\sin(360/365 \times JDAY) \quad \text{Eqn. 7}$$

8.2 Relating Minimum Polish Value to Terminal Skid Resistance

The remaining model to develop is one to link the laboratory-derived minimum polish value, PV, to terminal skid resistance. The two preceding analyses demonstrated that a reasonable procedure to estimate each of these parameters has been developed. PV is estimated as the asymptote of the accelerated polishing curve, and SN_{terminal} is estimated as the residual skid resistance of well-worn pavements after adjustment for seasonal effects. These values were estimated for each of the 26 pavement sections and aggregate samples described earlier.

A plot of these estimated terminal skid values versus the minimum polish value is presented in Figure 10. Some trend is observed, SN_{terminal} increasing as PV increases, although a high degree of variability is also indicated. Two models were considered to fit these data; a linear and a nonlinear model.

The linear model proposed for this relationship is the result of a simple regression analysis performed on SN_{terminal} and PV. The best fit for the data using the linear model is shown in Equation 8.

$$SN_{\text{terminal}} = 1.37PV - 0.5 \quad \text{Eqn. 8}$$

where SN_{terminal} = estimated terminal value of skid resistance

PV = estimated minimum polish value

This regression line, shown in Figure 10, trends through the data mass, but a great deal of variability about the line is observed. Not surprisingly, the correlation coefficient for this regression is low, $R^2 = .18$. However, the PV-SN_{terminal} relationship expressed in Equation 8 is statistically significant. This indicates that a higher degree of correlation may be achieved with a larger data base.

In an attempt to improve the correlation, a non-linear, exponential model was proposed. This nonlinear model is shown in Equation 9.

$$SN_{terminal} = C_0(1 - e^{C_1 PV}) + C_2 PV \quad \text{Eqn. 9}$$

where SN_{terminal} = estimated terminal value of skid resistance

PV = estimated minimum polish value

C_0, C_1, C_2 = nonlinear regression coefficients

This model basically represents a slightly bent line with slope equal to C_2 and passing through the origin. The best fit to this data set using this model has been achieved with the estimated coefficients presented in Equation 10.

$$SN_{terminal} = 12.4(1 - e^{-0.023PV}) + 1.15PV \quad \text{Eqn. 10}$$

Relationship Between SN terminal Value and Minimum Polish Value

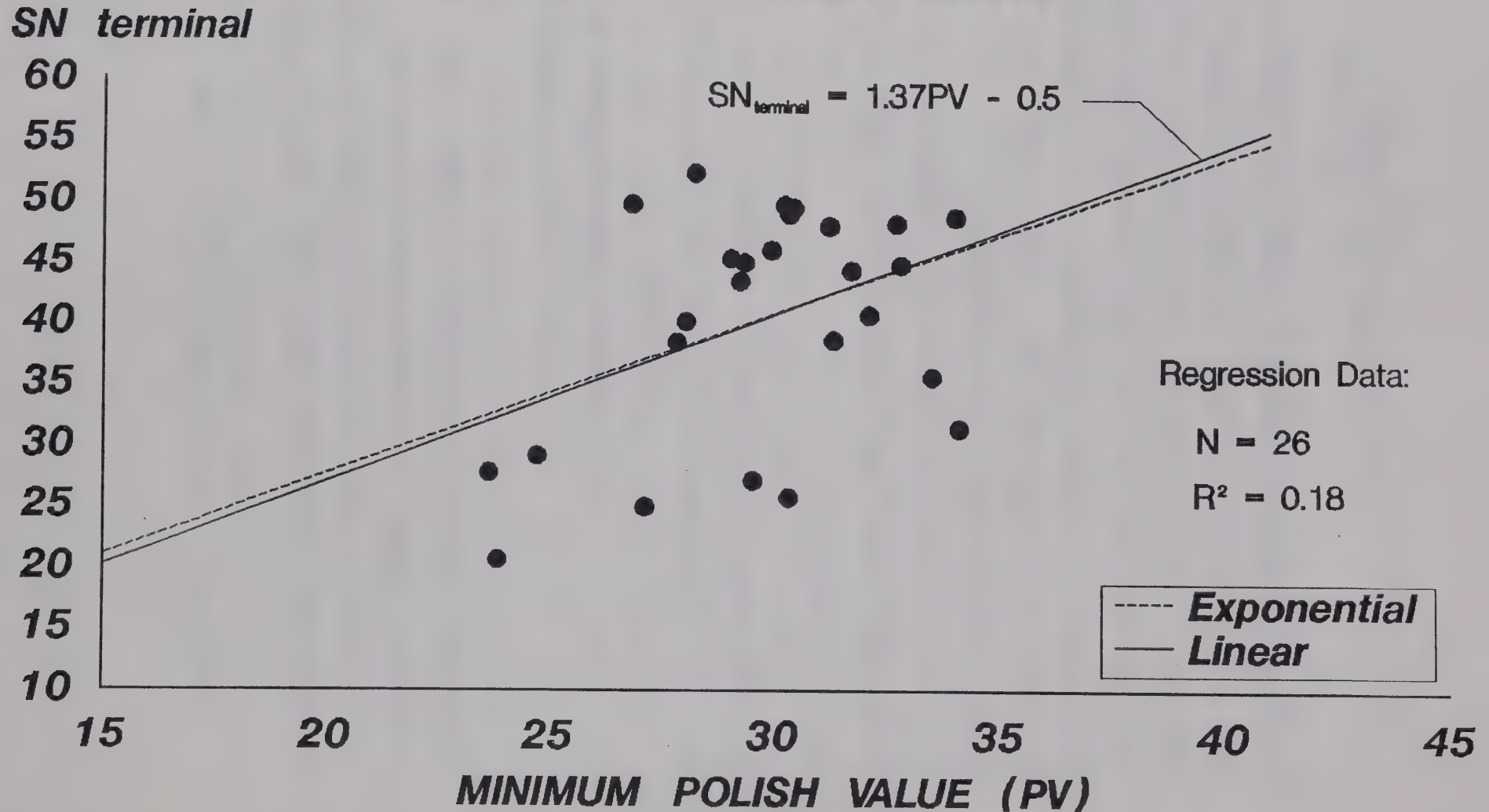


Figure 10

Assessment of the goodness of fit in nonlinear regression is less direct than in linear regression because conventional measures, such as the R-Square statistic, are not strictly applicable. However, the graphical demonstration of the two models compared to the paired data points shown in Figure 10 indicates that the exponential model is not significantly better than that deduced for the more direct linear model. Therefore, the linear model was chosen as that which best characterizes the relationship between the terminal value of skid resistance and the associated minimum polish value for surface course aggregates.

9.0 Application of Research Findings

As indicated earlier in this report, the ultimate goal of this research was to develop an acceptance procedure for prequalifying surface course aggregates on the basis of their long-term skid resistance potential. From the first phase of this study, a simple rank-order method of comparing aggregate samples is proposed. In the second phase, a more complex method, predicting the terminal skid resistance serviceability of a pavement based on the surface course aggregate's minimum polish value, is examined.

9.1 Phase 1 Acceptance Criteria

Having selected Model II as that which most accurately

describes the aggregate polishing curves for those samples under study, the aggregate sources can be ranked according to their polish resistance. The range for the minimum polish value, PV, for each of the samples tested (95% confidence level) is illustrated in Figure 11. The overall ranking of PV for each aggregate type follows. The range given in the list below represents the overall range of polish values determined at the 95% confidence level for the aggregates tested within the five aggregate type groupings.

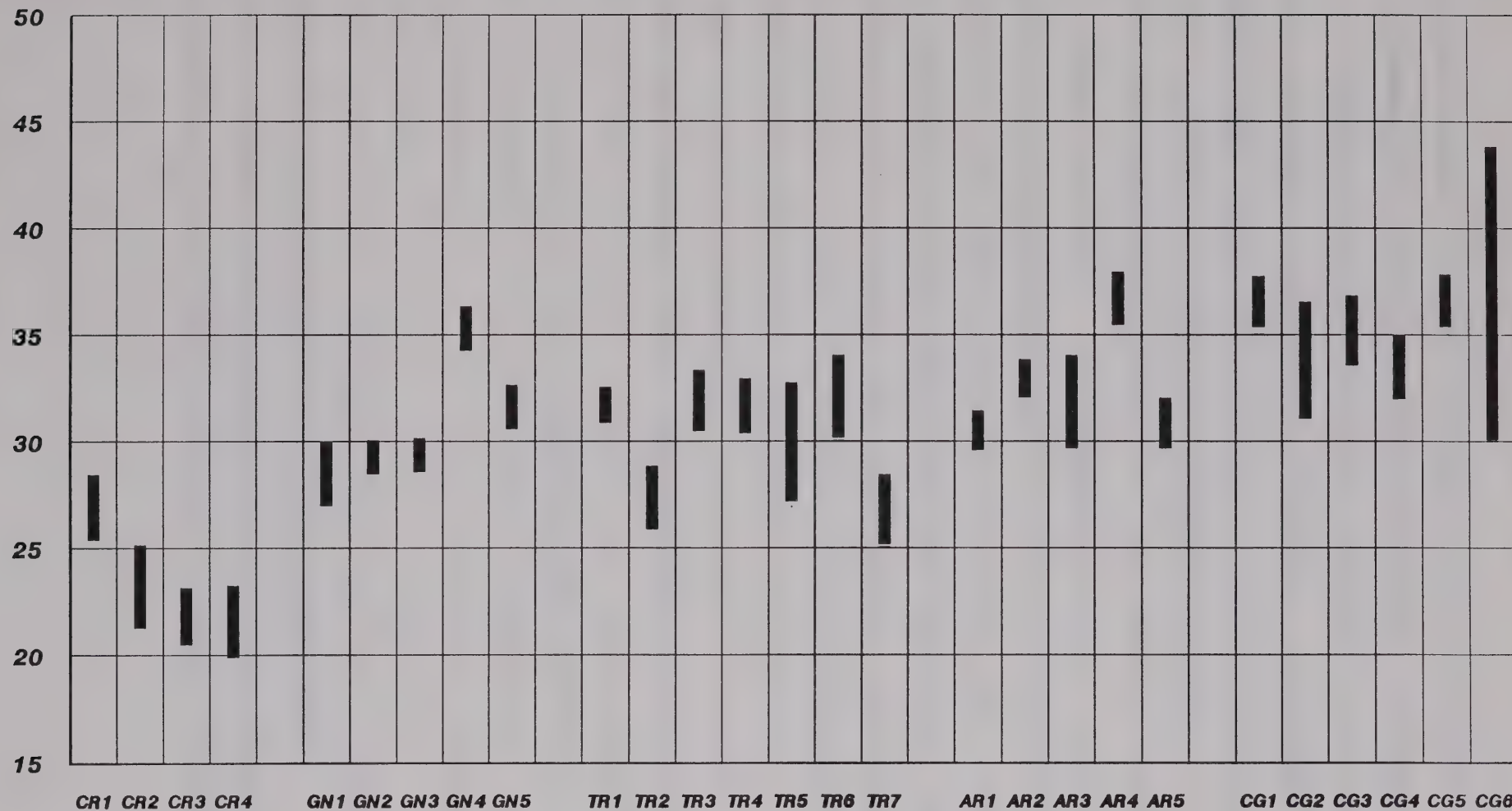
<u>Aggregate Type</u>	<u>Polish Value Range</u>
Carbonate Rock	20 - 28
Traprock	25 - 34
Gneiss	27 - 36
Argillite	30 - 37
Crushed Gravel	30 - 43

Immediately evident is that on the average, the crushed gravel samples exhibit high PVs and the carbonate rock samples exhibit low PVs. Traprocks, gneiss, and argillites are distributed within the intermediate ranges.

These results are not surprising. Based on New Jersey's experience with skid resistance, it is well documented that crushed gravel mixes yield superior skid resistance, while carbonate rock mixes provide marginal skid resistance over the long term (7,8). Currently, New Jersey Standard Specifications require that either open-graded mix or crushed gravel

FIGURE 11
MINIMUM POLISH VALUES AT 95% CONFIDENCE LEVEL

POLISH VALUE



NOTE: SAME QUARRY- TR4 EXTRACTED, TR6 STOCKPILED
SAME QUARRY: AR1 FROM '83, AR5 FROM '84
MULTIPLE CG SAMPLES FROM SAME STOCKPILE

(containing no more than 10% total carbonates) be used when bituminous friction course is specified. In general, carbonate rock is excluded from use as coarse aggregate in surface course mixes. Therefore, the results obtained in this phase of the study support New Jersey's current specifications.

The study results also indicate, however, that considerable variability of polish resistance can be expected within a given aggregate type. The broad range of polish values shown in Figure 11 indicates that there may be acceptable and unacceptable sources of the same aggregate type. The polishing wheel test method and data analysis procedure presented in this report can be used to distinguish between these aggregate sources.

By applying "historical perspective" to the data shown in Figure 11, tentative acceptance criteria for the minimum polish value permitted for surface course mixes can be inferred.

<u>Minimum Polish Value</u>	<u>Quality</u>
24 or less	POOR
25 to 30	MARGINAL
31 or more	GOOD

This simple table can enable the materials engineer to select surface course aggregates on the basis of a quantitative test method, restricting the use of "poor" aggregates to

low-volume roads, "marginal" aggregates to moderate-volume roads, and requiring a minimum polish value of 31 for general use.

It is emphasized that these limits are offered only as a starting point for future refinement. In the next section a more rigorous treatment of the data generated from both phases of the study is presented.

9.2 Phase 2 Acceptance Criteria

Using the relationship between the laboratory-derived minimum polish value and the terminal value of skid resistance (Eqn. 8), to develop acceptance criteria for surface course aggregates is more complicated, and will require refinement to the statistical model prior to implementation. The variability in the model in its present form does not permit its application at this time. By increasing the size of the data base (by collecting additional aggregate-specific skid resistance data over time) it may be possible to develop a precision statement that will permit the use of the relationship between SN_{terminal} and PV for developing acceptance criteria.

By the way of an illustration, the model in its present form, with the application of two additional adjustments, can be used to conceptually demonstrate how an acceptance plan may be developed. The first adjustment is needed to account

for seasonal variations in the in-situ measured skid number. The second adjustment is needed to account for inherent variability in the PV/SN relationship. This conceptual acceptance plan is illustrated in Figure 12.

For example, to ensure that at no time, a pavement's skid number at 40 mph is less than 35, the first adjustment must be applied to account for seasonal variations in the measured value. The sine wave function for skid resistance shown earlier in Figure 9 indicates that, depending on the date of test, an SN_{terminal} value of 38 is needed to ensure measured skid numbers in excess of 35 throughout the annual cycle.

Substituting this value for SN_{terminal} into Equation 8 yields a required minimum polish value of 28 for the surface course aggregates in the mix. However, in order to account for the variability in the model, a second adjustment must be made. This second adjustment would depend on the confidence limits established for the model (for good correlations, 95% confidence is usually accepted). In this example, the 75% confidence level is used. In order to factor in this confidence limit, it is necessary to adjust the line of acceptance 7 units below the best fit relationship. This corresponds to a 5 unit increase in PV. Using this more conservative model, a minimum polish value of 33 would be required to ensure year-round SN40s of greater than 35.

Conceptual Acceptance Plan For Surface Course Aggregates Based On Minimum Polish Value

SN terminal

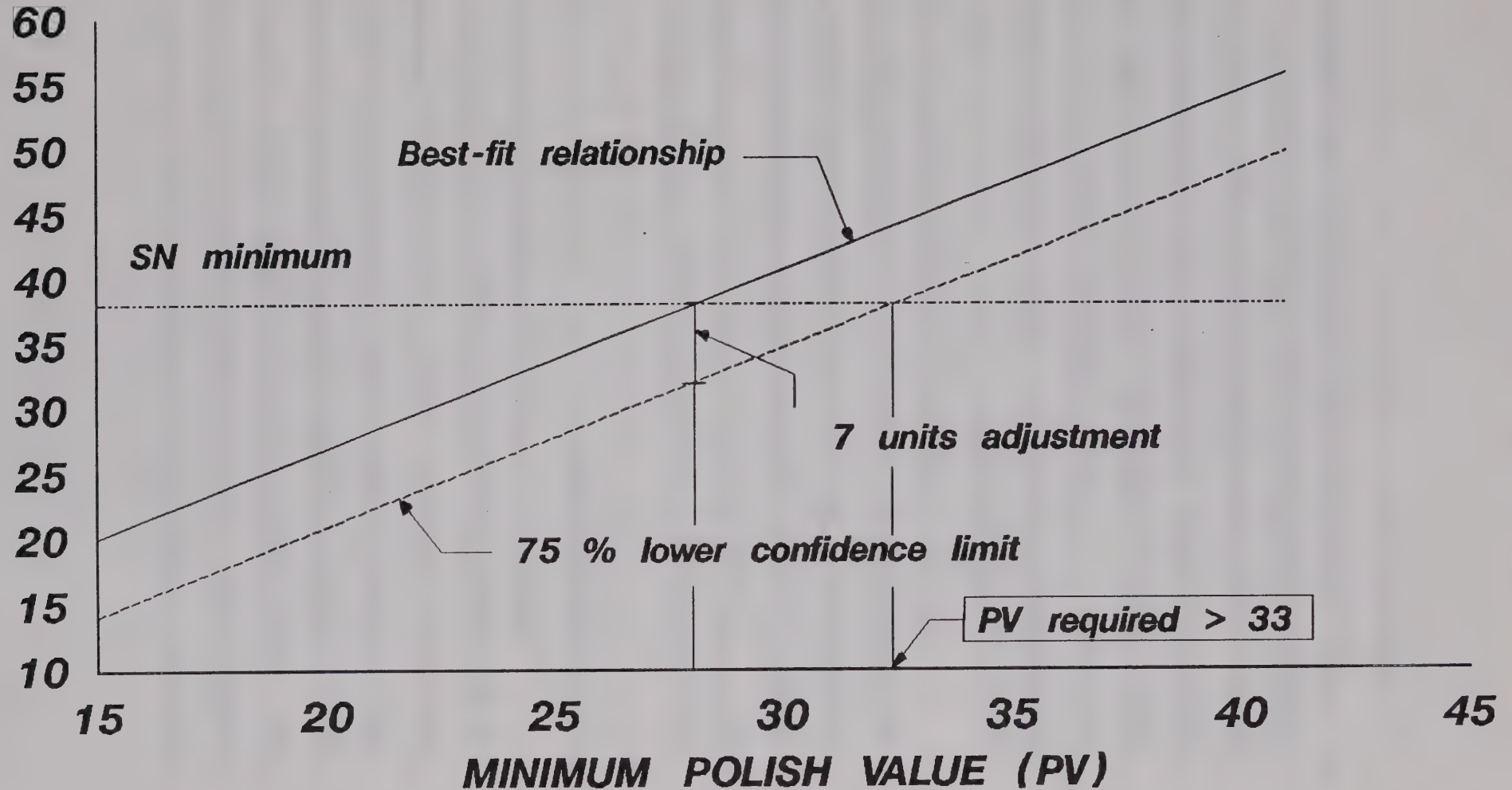


Figure 12

10.0 Conclusions

The successful application of an accelerated laboratory test method to identify the polish resistance of various aggregates was demonstrated in the first portion of this study. This development alone permits the ranking of potential surface course aggregates on the basis of their resistance to polishing. A more rigorous method of determining an aggregate's suitability for use in surface course mixes has thus been established.

In the second phase of this study, a rational model was developed to account for the effects of aggregate characteristics and seasonal fluctuation on field skid resistance. However, the inherently large variability observed in SN_{terminal} -PV relationship prohibits the development of an acceptance plan based on the model at this time.

11.0 Recommendations

Additional research is required prior to implementing an acceptance program for surface course aggregates based on laboratory polishing tests. The tentative acceptance criteria proposed in section 9.1, if applied, would represent a major change in the Department's Materials testing procedures and acceptance policies, and should be examined in more depth. More attention should be devoted to integrating the minimum polish value criteria with existing aggregate

identification tests (i.e., LA Abrasion and % Absorption), in order to ensure the overall quality of surface course aggregates. In addition, more work is needed to develop a sampling plan for accelerated polishing acceptance testing, based on source variability, as well as test variability. And, the test method itself requires simplification, specifically in the areas of sample preparation and data analysis (non-linear regression). These difficulties may be overcome with a relatively small research effort.

The information acquired in the second phase of this study shows promise and should be investigated further. In its present form, the model proposed for the relationship between minimum polish value and terminal skid resistance is not acceptable for use. However, improvement of this model may be achieved through developments in the following areas.

(1) A larger data base is essential. Continued investigation should seek additional aggregate test results and incorporate this information as it becomes available.

(2) The amplitude of the seasonal fluctuation in skid number has been expeditiously assumed constant, even though some evidence suggests that it varies with aggregate type. A laboratory test procedure capturing this effect would be desirable. One possible test would be to measure the difference in polish values between samples at different temperatures to determine the change in minimum polish values,

and to incorporate this difference into the amplitude coefficient. Another factor that was not considered in this analysis was the effect of mix design on the seasonal fluctuation of skid resistance. In future field experiments, it would be useful to collect a substantial amount of data (skid resistance, macro and microtexture, precipitation, air and surface temperature) over time, holding mix design and aggregate type constant.

(3) It is possible that the polishing action of traffic is less abrasive than the polishing action of the British Polishing Wheel. If this is so, the terminal skid resistance values in the field may never reach the asymptote estimated in the laboratory model. In this case, a laboratory polish value greater than the asymptotic value would actually be more meaningful. Further study is warranted in this area.

(4) A continued effort must be made to verify the integrity of measured skid resistance values. Variability of field measurements of skid resistance may simply be inherent to the test, or the 'true' SN40 may be fundamentally elusive to measure. This point may become even more critical in the future, as New Jersey is beginning to recognize the future need for self-calibration of its skid test equipment. Research will be required to verify the skid test measurements made at present, as well as to ensure their future accuracy.

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